TRANSMISSION OF NIAGARA FALLS POWER TO CHICAGO, ILLINOIS

BY
L. H. ROLLER

ARMOUR INSTITUTE OF TECHNOLOGY

1912

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THE TRANSMISSION OF NIAGARA FALLS POWER TO CHICAGO.

A THESIS

PRESENTED BY

Louis Herman Roller,

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

HAVING COMPLETED THE PRESCRIBED COURSE OF STUDY IN

ELECTRICAL ENGINEERING

May, 1912.

Approved
E. H. Freeman
Prof. of Elect. Engineering

H. M. Raymond
Dean. Eng. Studies

L. C. Monin
Dean of Cultural Studies.

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LETTER OF TRANSMITTAL.

May, 1912.

To the President and Faculty
of Armour Institute of Technology.

Gentlemen:

I have the honor to submit herewith a thesis, entitled "The Transmission of Niagara Falls Power to Chicago", for the degree of Bachelor of Science in Electrical Engineering.

The transmission of Niagara Falls power to Chicago is a possibility but not a probability for reasons both political and economical. However, the problem here presented has proven of especial value in pointing out the various considerations involved in attempting to overcome the difficulties of high-tension power transmission; until the economic conditions of the country render the extra-long-distance transmission of power financially successful, the practical engineer will have little occasion to deal with such difficulties as those pointed out, although the research engineer is already at work upon some of them.

Respectfully,

L. H. Roller.

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THE TRANSMISSION OF NIAGARA FALLS POWER TO CHICAGO.

INTRODUCTION.

Long Distance Electric Power Transmission.

All science is based upon the two ideas of matter and energy, matter being defined as "anything which occupies space", and energy being defined as "that property of matter which gives it motion and makes it active". The great theory of the conservation of energy tells us that the total energy in the universe is constant, and that the apparent expenditures of energy which are continually going on are in reality only transformations of energy; in other words, energy is never used up, but is being constantly transformed and transmitted. The word "power" is defined as "the rate of flow of energy" or "the rate of doing work", although the use of the word power as a synonym for energy is common. The term "transmission of power" as here used will be defined as the transmission of energy in the form in which it is to be utilized, which is the kinetic form as distinguished from the latent.

The use of power is something which has always engaged the attention of man because power is manifest in everything which goes to make up his

existence on earth, and it is because of his ability to make intelligent use of power that he is able to dominate to some extent over the lower forms of life and the forces of nature.

Man's knowledge of the uses of fire and water in transforming energy from its lowest form, heat, to a form in which he could use it as power, developed a field in which the application of power was of fundamental importance. In the age of steam the distances between the places where the power was developed and where it was utilized were measured in hundreds of feet, since the transmission was effected by mechanical means. However, this was but the first step in power transmission.

The application of electricity to power transmission opened up a vast field and presented possibilities which could never have been realized with steam. One of the first notable examples of electric power transmission over a distance took place some thirty years ago, when a French scientist supplied energy from a generator to a motor over about five miles of iron wire with a loss of about fifty percent of the generated power. This feat brought the attention of engineers to long distance power transmission, with the result that the subject received, and still receives, a great deal of study and investigation, and is now considered one

of the most important branches of electrical engineering.

The distances of electric power transmission, at first expressed in miles, are now spoken of in terms of hundreds of miles. Transmissions up to one hundred miles in length are common, while two hundred mile, three hundred mile, and four hundred mile transmissions are in use, with transmissions up to seven hundred miles receiving the consideration of present engineers. The conditions which are responsible for these long distances of power transmission are primarily a large source of cheap power at a great distance from a market for the power. The sources of cheapest power are the great water-falls and large rivers and lakes offering a considerable head, while the greatest markets for power are large manufacturing and industrial centers located in the large cities. Thus we find over all of the Christian world transmission systems connecting the water powers with the large cities,- all being the result of development in the last twenty years.

The principles of long distance electric power transmission are best brought forth in the consideration of an actual example, and for this purpose transmission from the largest water-fall, Niagara Falls, to the second largest city, Chicago,

will be taken as a typical example of long distance electric power transmission in the United States.

Problem.

The problem herein discussed will be the transmission of power from a hydraulic station located at Niagara Falls to a transformer sub-station located in Chicago, the size of the hydro-electric generating station to be such as to give a full-load output of one-fourth million kilowatts. The quantity of power receivable at the substation will be calculated, with its cost at the low-tension bus-bars, for several different systems of transmission employing different high-tension voltages at the generating station; and the operating and economical characteristics of the various systems will be compared.

The sub-station load will be assumed to be of such character that the load factor, which is the ratio of the average load to the maximum load during the day, will have an average value of one-half.

THE GENERATING STATION AT NIAGARA FALLS.

Location.

Several miles below Niagara Falls the Niagara River makes a turn which is almost a right angle; in other words, it changes its course rather abruptly from a northwesterly direction to a northeasterly direction. The river at this point, and for a distance above and below, flows through a sort of gorge, that is, the banks are high and steep, and the drop in head is considerable. This point is most desirable for the location of the generating station, for, by building it below the bend in the river, on the American side, a canal may be run straight back from it to a point either above or just below the Falls, and the water conveyed at an elevation above the adjacent river to the station, where it will be returned to the river after passing the turbines through the tunnel tail race.

Cost of the Generating Station.

The report of the Ontario Power Commission gives the detail estimated capital costs of hydroelectric plants at Niagara Falls for sizes of 50,000 75,000 and 100,000 horsepower at the turbines. These figures have been analyzed, and from them

estimates have been made for stations having a turbine horsepower up to four hundred thousand.

The capital costs may be divided into two classes,-those independent of the output of the station, and those which vary in some way with the output. The latter are again sub-divided into two classes,- one varying directly with the output, the other varying as some power of the output less than unity.

The capital costs which are independent of the output are the cost of headworks and canal, tunnel tail race, office buildings and machine shop, and miscellaneous items.

(1) Headworks and canal	$ 1,250,000
(2) Tunnel tail race	450,000
(3) Office building and machine shop	150,000
(4) Miscellaneous	150,000
	$ 2,000,000

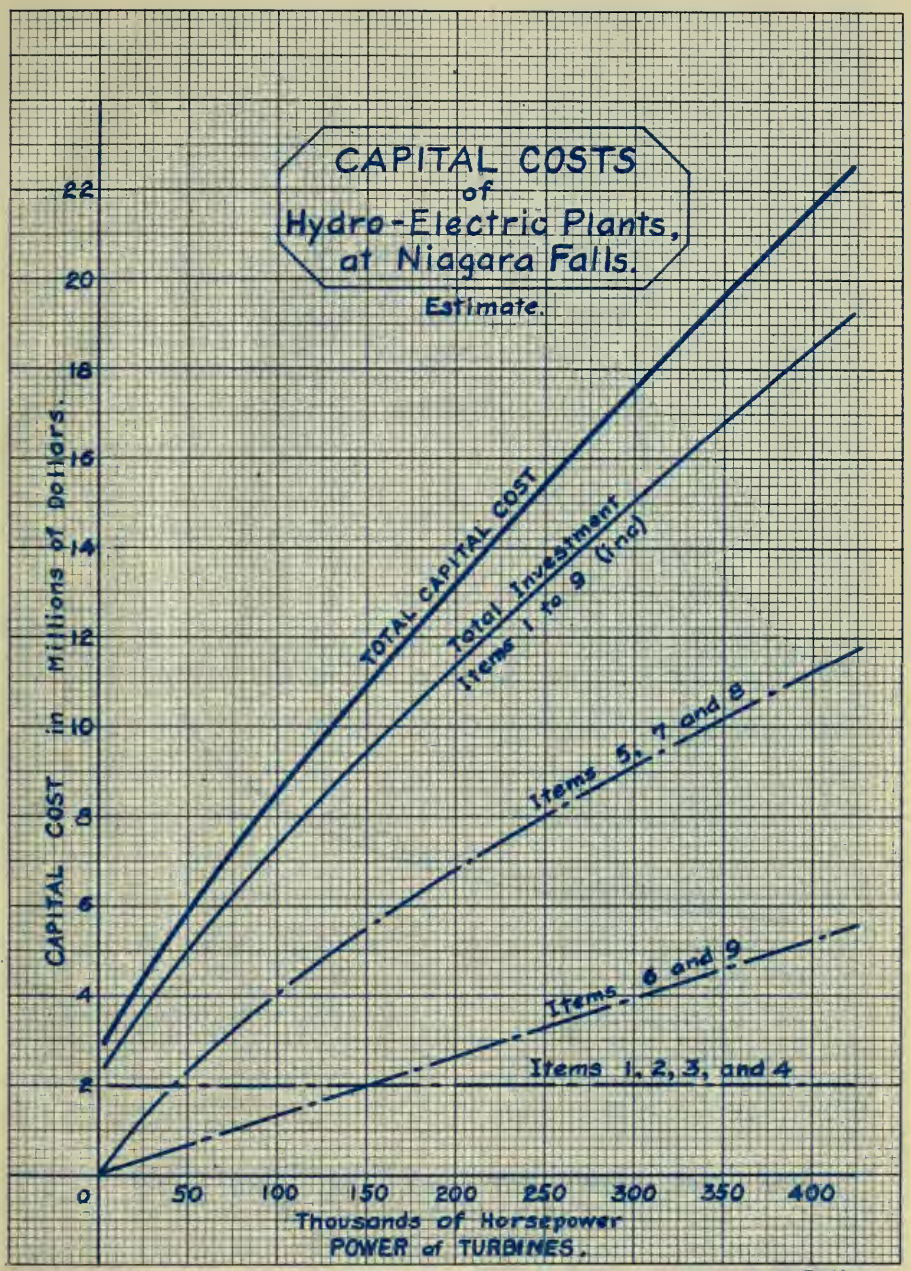
The costs which vary direct with the size of the station are the cost of power house and transformer station and equipment, while those which vary as some power of the size less than unity are the costs of wheel-pit, hydraulic equipment, and electrical equipment.

Size of Plant, HP	50,000	75,000	100,000
(5) Wheel-pit $	500,000	700,000	700,000
(6) Power house	300,000	450,000	600,000
(7) Hydraulic equipment	1080,000	1440,000	1980,000
(8) Electric equipment	760,000	910,000	1400,000
(9) Transformer station and equipment	350,000	525,000	700,000
$	2990,000	4025,000	5380,000

Plotting these cost items against power of turbines, we get the curves shown in Fig. 1, the items being put into three groups as shown, and three curves being drawn from the extensions of which the costs of the groups are determined for any size of station up to 400,000 horsepower. The summation of these items gives the total investment curve. To the total investment ten percent is added for engineering and contingencies, and to this is added the interest during construction, which is taken for two years at four percent per annum, the final value giving the total capital cost curve.

From the total capital cost curve of Fig. 1 a capital cost per horsepower curve is plotted, as shown in Fig. 2, which shows the decrease in capital cost per horsepower as the size of the station is increased.

From the curves of Figs. 1 and 2 the capital cost of a 250,000-kilowatt or 335,000-horsepower hydroelectric plant at Niagara Falls will be seen to be in the neighborhood of $ 19,000,000.



L. H. Roller.

Fig. 1.

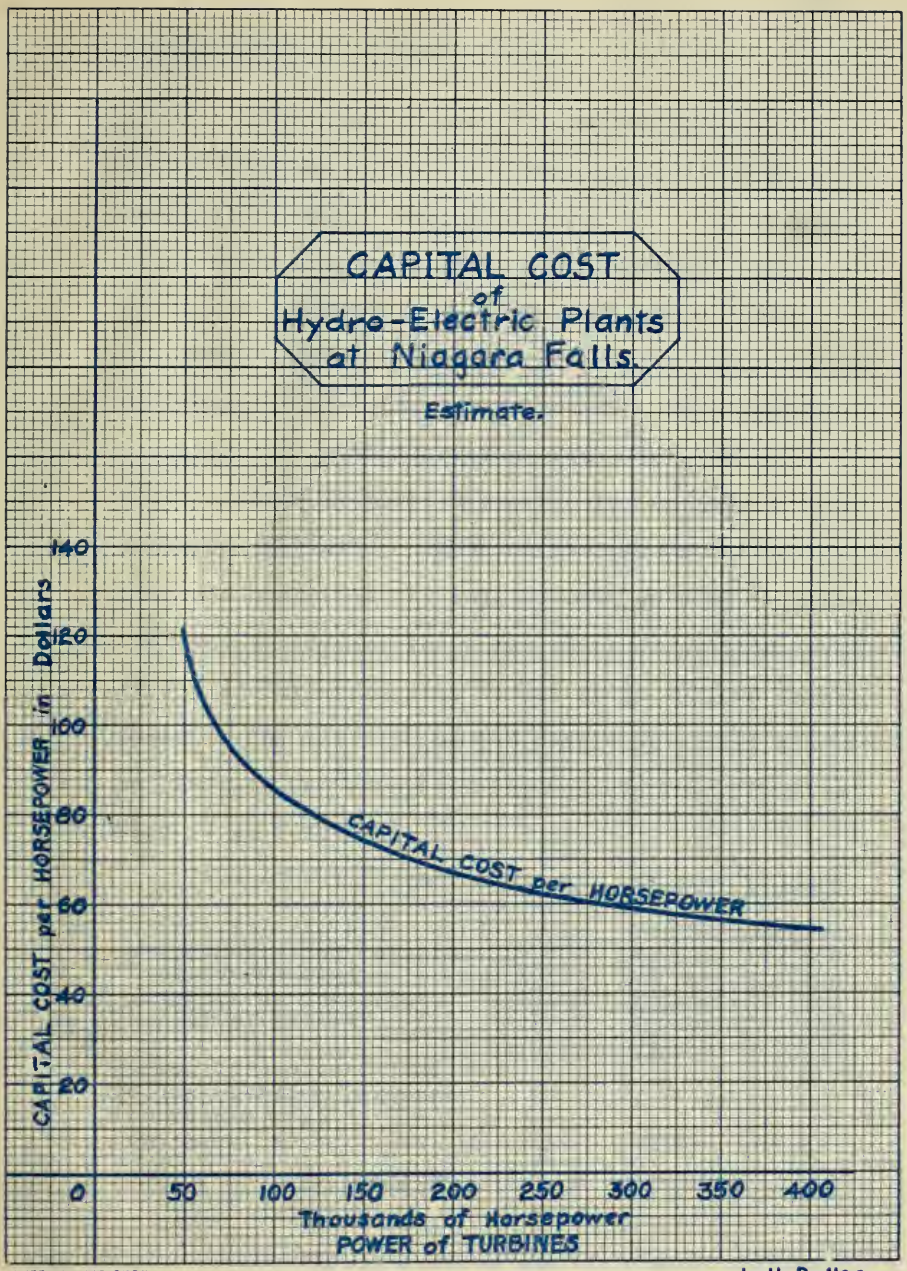


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Fig. 2.

Cost of Power at Niagara Falls.

The cost of power is determined by the annual charges against the hydro-electric plant, an analysis of which is shown in Fig. 3. The greatest of these is the interest on the investment, the curve for which takes the same form as the total investment curve of Fig. 1. The other items are maintenance and repairs, replacement fund, rental of water, and administration, etc., for each of which a curve is plotted showing its variation with the size of plant. These curves were obtained in the same manner as the capital cost curves, by plotting the values for the three sizes of stations given, and extending the curves up to 400,000 horsepower. The estimate of the yearly operating charge as given in the report of the Ontario Power Commission is as follows:

Size of plant, HP	50,000	75,000	100,000
Administration, etc.	$ 57,900	70,200	86,300
Maintenance and repairs	115,700	140,400	172,600
Replacement fund	86,800	105,300	129,500
Interest on investment	231,400	280,800	345,200
Rental of water	52,500	65,000	77,500
	$ 544,300	661,700	811,100
Taking losses as 2 1/2% to high-tension bus-bars the yearly cost of 24-hour power is	$ 11.16	9.05	8.32
or in % of capital cost	9.62%	9.63%	9.67%

In Fig. 4 a curve for the annual operating expenses in percent of the capital investment

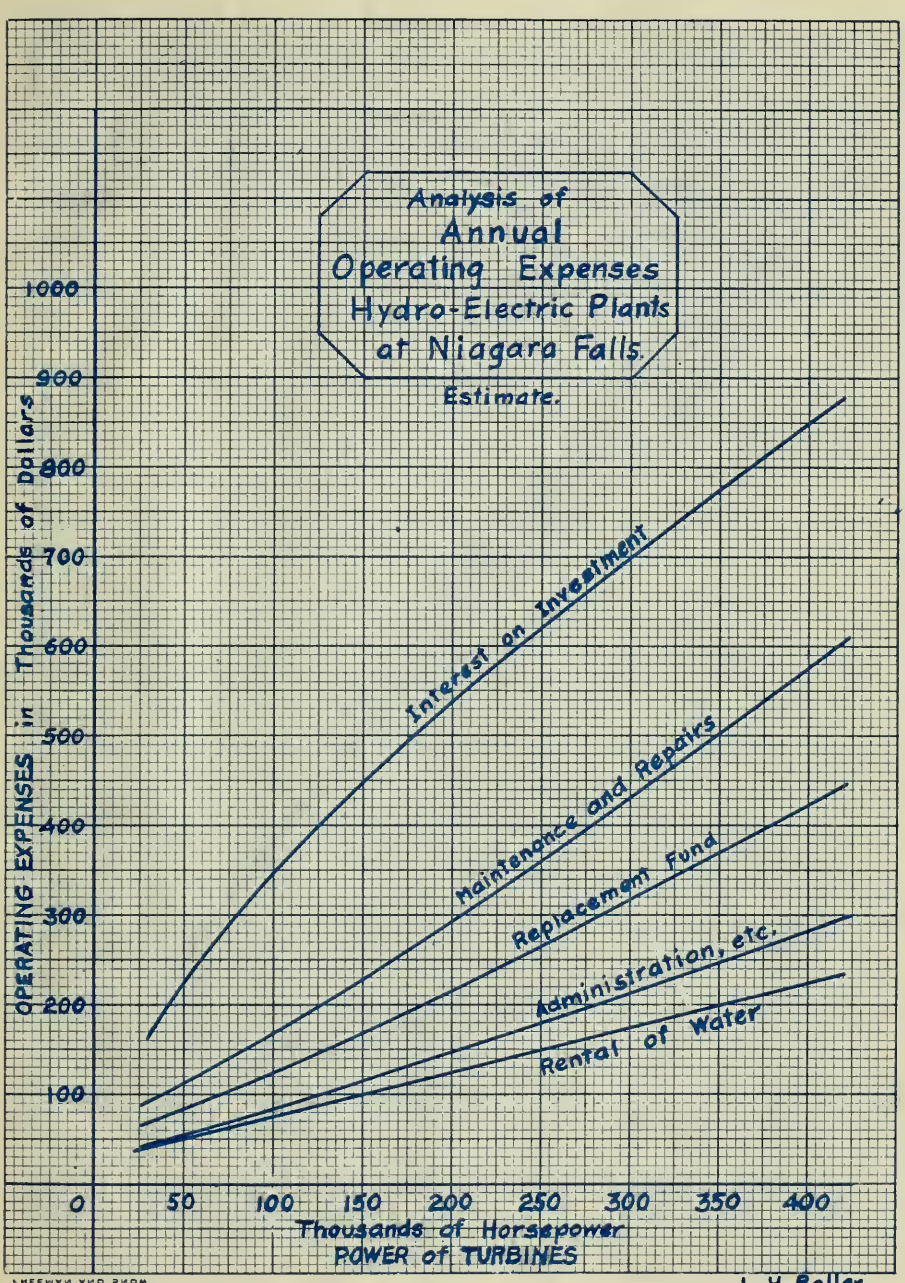

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Fig. 3.

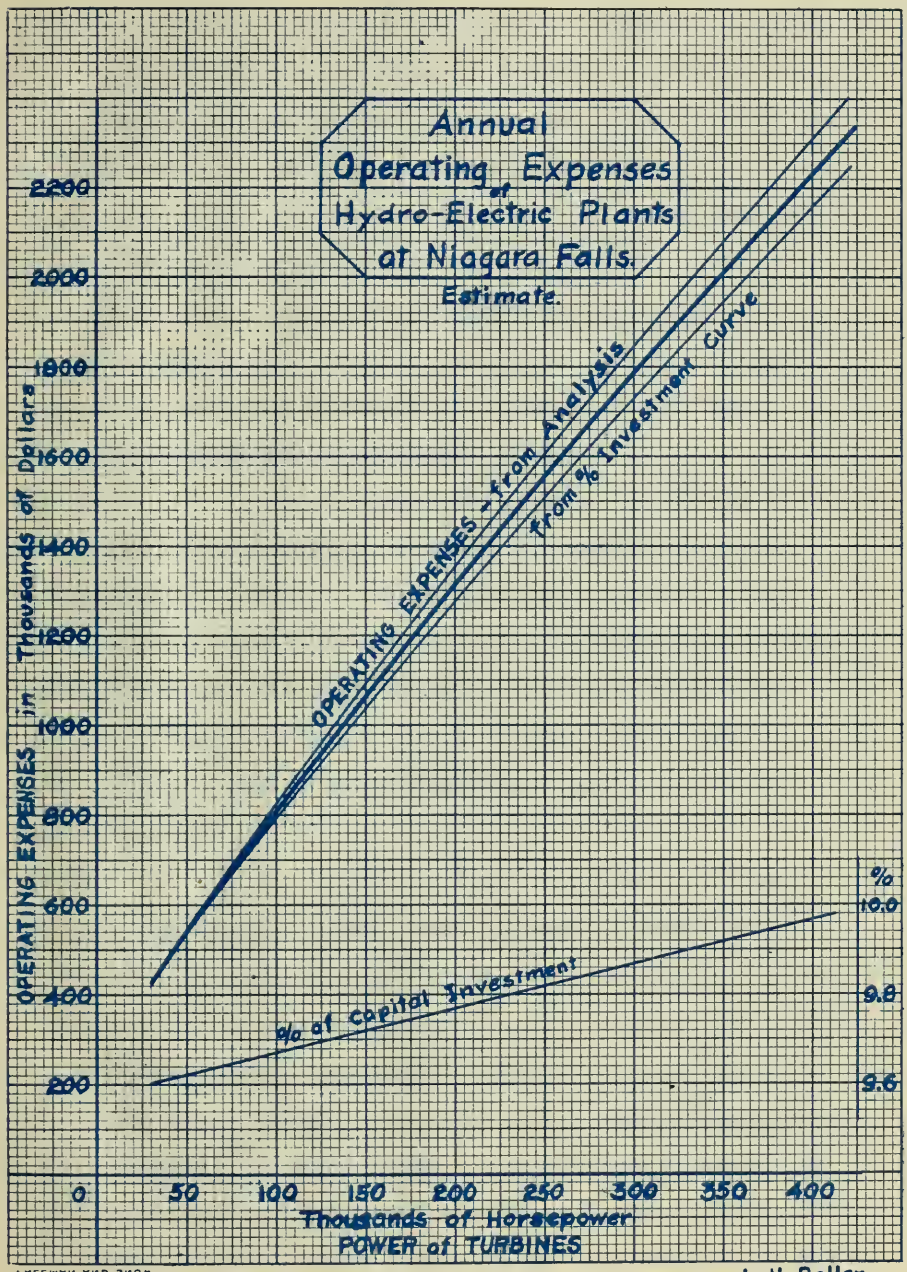

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Fig. 4.

is plotted, by means of which the percentage may be determined for any size of station. From this a curve of total operating expenses is calculated and plotted. Further, the items plotted in Fig. 3 are summed up, and a curve plotted, Fig. 4, showing the operating expenses from this analysis. Then from these two curves, which agree quite closely, although derived in different ways, the final curve for operating expenses is taken as the average, being plotted as the heavy line of Fig. 4.

From the curve of Fig. 4 the curves of Fig. 5 are plotted, showing the annual cost of 24-hour power at the high tension bus-bars, for various sizes of stations, in terms of both horsepower and kilowatt output. In these curves an allowance of five percent is made for losses of power between the turbines and the high-tension bus-bars.

The curves of Fig. 6 are derived from those of Fig. 5 and show the cost of power at the high-tension bus-bars of the 250,000-kilowatt plant, in cents per kilowatt-hour and in dollars per kilowatt-year, for various values of the load factor. The curve showing the cost in dollars per installed kilowatt per year shows the slight decrease in the cost of operation at the lighter loads, the percentage decrease being taken the same as that shown by

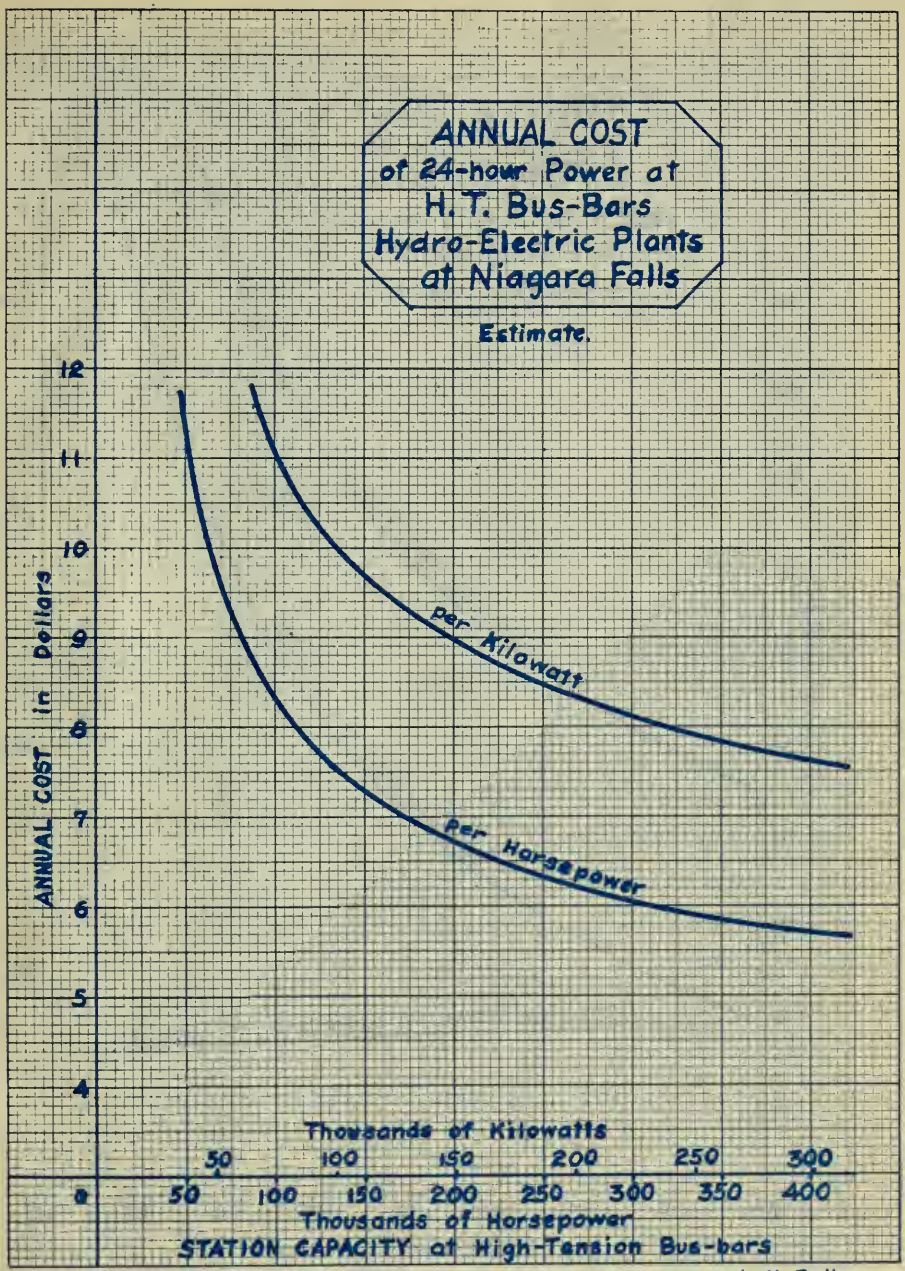

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Fig. 5.

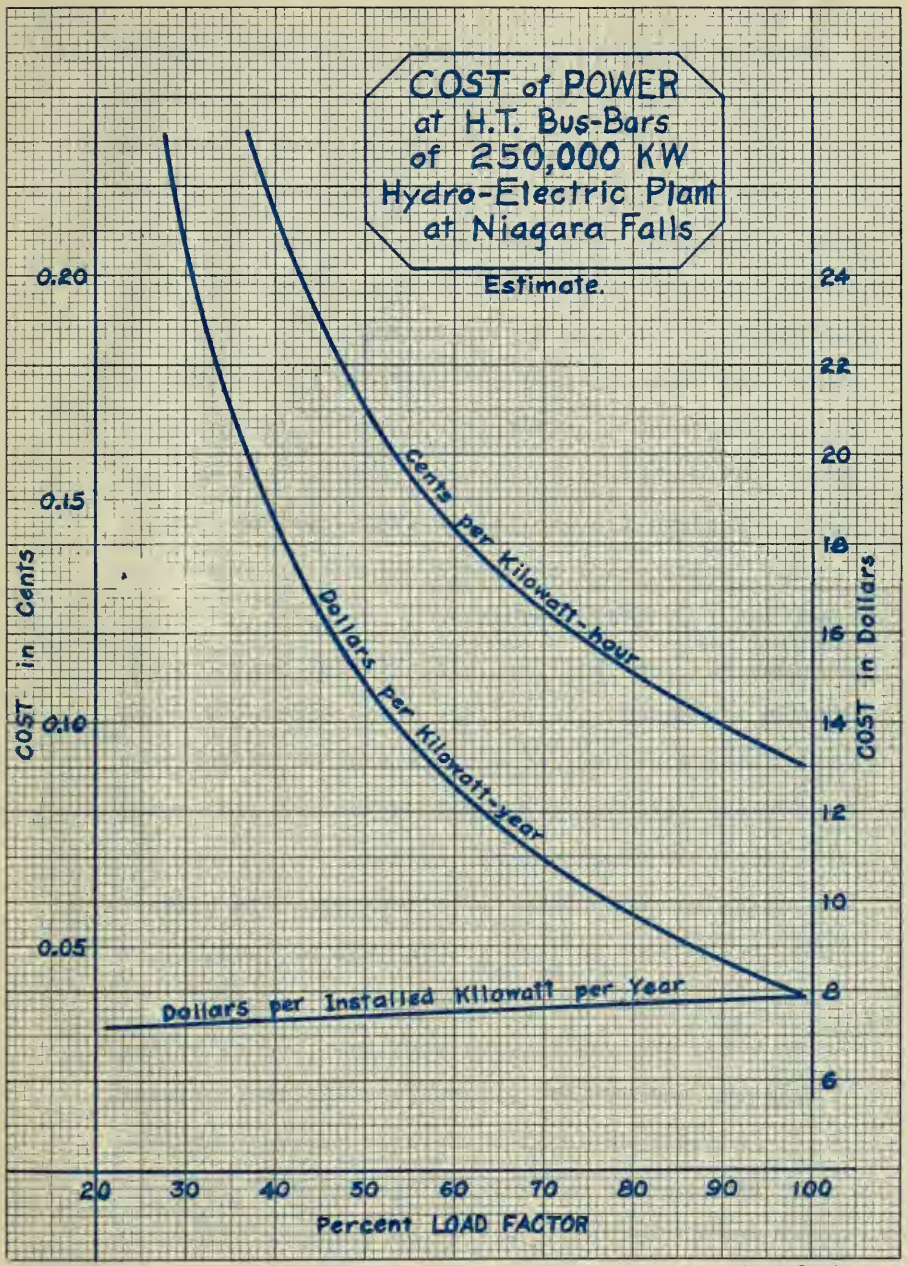

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Fig. 6.

Stott in estimating the cost of power for a hydro-electric station. The cost curves take this decrease into consideration.

In considering the cost of power the foregoing estimates have been made upon the assumption that the high-tension bus-bar voltage was one hundred kilovolts or thereabouts. To make the determination as complete as possible the cost of power for higher voltages will also be calculated. According to Sheldon and Hausman the cost of transformers, lightning arresters, choke coils, and oil switches increases in direct proportion to the voltage, for practical purposes. Going back to Fig. 1 and the accompanying detail costs, we find that the cost of item (9), transformer station and equipment, amounts to about $2,370,000 for the 335,000 horsepower plant. Since this is for one hundred kilovolts, the cost of the transformer station and equipment for three hundred kilovolts would be three times as much, or $7,110,000, an increase in capital cost of $4,740,000. Adding the ten percent for engineering and contingencies, and four percent for two years as interest during construction, we get the increase in total capital cost to be about $5,600,000. Carrying this through we find the increase in operating expenses to be $240,000, making the annual cost of 24-hour power $8.72 per kilowatt. (Fig.7.)

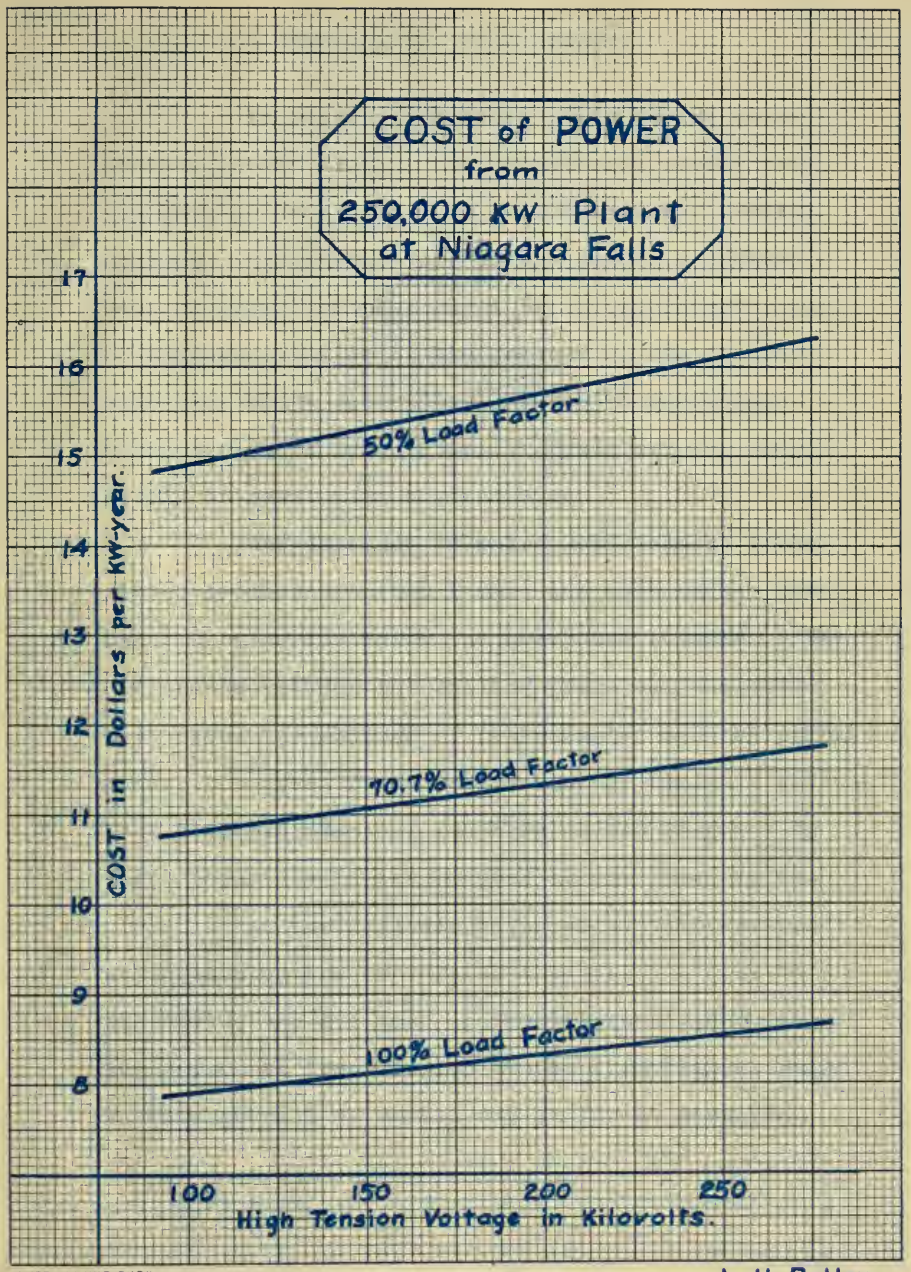

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Fig. 7.

THE TRANSMISSION SYSTEM:

In any long-distance power transmission of hydro-electric energy the transmission system plays the most important part in the matter of financial success. Hydro-electric energy can be generated very cheaply in almost any locality where water-power is abundant, but it is the economy of the transmission line which determines between long-distance transmission of hydro-electric power and the local supply of power from a steam plant.

The distance to which power can be transmitted depends upon two items; the cost of the power and the price for which the power can be sold. The difference between the selling price and the cost must cover the expense of transmission and the profit; hence, the greater this difference or the more economical the transmission, the greater the distance to which power may be transmitted at the same profit.

In the following discussion the factors which make up the expense of transmission will be set forth, and the most economical conditions for a long-distance transmission system from Niagara Falls to Chicago will be worked out as far as possible.

Location of the Transmission Line.

The first consideration in the transmission of power between two points is the route of the transmission line. The selection of a route will be governed by conditions of topography and climate variations principally. The country in the neighborhood of the Great Lakes is quite level, and no exceptionally severe climatic conditions are encountered. Hence the most direct route from Niagara Falls to Chicago is the most desirable.

Reference to the map of Fig. 8 will show that there are two possible routes which appear to be the most direct; one, crossing at Niagara Falls into Canada and returning to the United States in the vicinity of Detroit and thence to Chicago; the other, passing around Buffalo and following the south shore of Lake Erie until the latitude of the lower end of Lake Michigan is reached, thence straight across to Illinois and up to Chicago. Of these two the latter is chosen as shown for the reasons that the right-of-way is entirely on American soil, and the crossings of the Niagara and Detroit Rivers are avoided.

By the route shown in Fig. 8 the line between Niagara Falls and Chicago will be 550 miles long. In the routing of a transmission system of this kind it is desirable to avoid all thickly

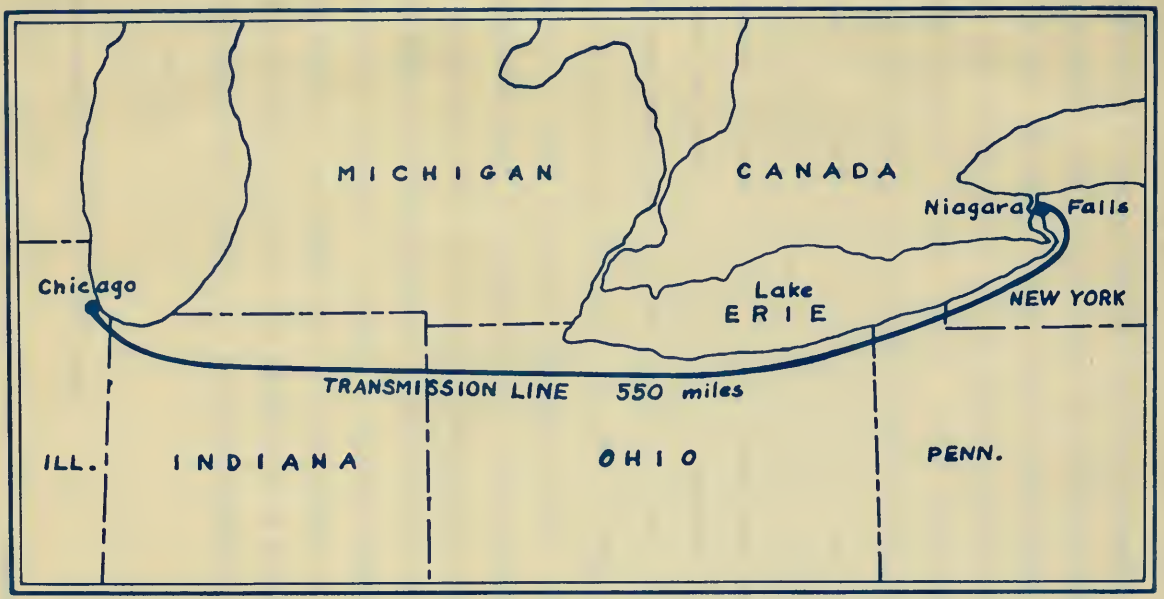

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Fig. 8.

Map showing Route of
PROPOSED TRANSMISSION LINE
Niagara Falls to Chicago

populated districts such as towns and villages, and the suburbs of large cities; and the presence of high-tension cables and towers in a large city is out of the question. Hence the right-of-way over which the conductors will be suspended will consist almost entirely of farm land. This right-of-way may be purchased, as it would be for railroads, or it may be rented from the owners, as is at present done in Ontario, Canada. As an average price on the value of this land we shall assume one hundred dollars per acre. This may be considered as the purchase price for a private right-of-way, or the capitalized rental price if the right-of-way is rented. It may seem that the rental price thus determined would be exceptionally low, especially as the rate of interest is to be taken as 4%,- which would mean a rental price of four dollars per acre per year. However, this will not seem such a low value when it is remembered that the owner of the land can still be given the privilege of cultivating all except that taken up by the tower bases and the patrol path.

Importance of Choice of Voltage.

The most important factor in transmission line economics is the choice of voltage. The ability to obtain from a single alternating current

machine, by means of the alternating current transformer, a voltage higher than it was practicable to generate directly, has made the alternating current far superior to the direct current in the matter of generation and transmission of power over long distances.

The importance of the choice of voltage lies in the fact that for the transmission of a given amount of power, the higher the voltage of transmission, the less the current in proportion to the first power of the increment and the less the transmission loss in proportion to the square of the increment in voltage. Were the matter of power loss in transmission the only item of consideration the economic voltage would be infinite. But there are practical limits to which the voltage can be raised, set chiefly by the matter of insulation of apparatus and lines, and the breakdown of the dielectric strength of air. The insulation of apparatus requires an expense in insulation beyond certain limits of voltage which is much greater than the saving effected in conductor material. The limit to the dielectric strength of air means that with a particular set of conditions there is a value of the voltage beyond which the air ceases to act as an insulator, the result being a loss of power by dissipation into the air.

The choice of voltage for long-distance transmission is thus not a simple matter. For a

definite and constant set of transmission conditions there is a certain value of the voltage which will prove most economical, and its value can be determined by making certain assumptions, but this is impracticable because the conditions for any system are not constant, and contain too many variables about which assumptions must be made. For the present purpose no one value of voltage will be determined as the most economical for the Niagara Falls to Chicago transmission, but several different values will be empirically chosen, and the details of transmission worked out for each one.

Number of Phases and Number of Circuits.

It is necessary, before determining upon the values of voltage to use, to know something of the amount of power to be transmitted over the system, and since the total amount supplied to the line is known, the number of phases and number of circuits will determine the amount per circuit, which standard practice dictates shall not be much greater than fifty thousand kilowatts.

In all cases where alternating current distribution or transmission is used three-phase systems are the most common, because single-phase and quarter-phase systems require one-third more conductor material than three-phase for the same

maximum voltage between wires and the same amount and percentage of lost power. Hence three-phase transmission will be chosen for this system, especially so since the cost of power was calculated for three-phase.

The practical limits of the amount of power per circuit would tend to fix the number of circuits at five for the transmission of 250,000 kilowatts. Since it is desirable to have two circuits per tower-line an even number of circuits will be used and six circuits will be decided upon, with the option of using four circuits if found desirable for the higher voltage lines.

Choice of Voltages.

According to Still an empirical formula which may be used in determining the voltage of transmission is

$$\text{pressure in kilovolts} = 5.5\sqrt{L}$$

where L is the length of transmission (miles) plus 1/200 th of the horsepower transmitted, account being thus taken of both length of transmission and power transmitted. Regarding choice of voltage Still says, (Electrical World, 58-746), "Given the amount of power to be transmitted and the length of line, one can with the aid of the formula decide upon a standard voltage and proceed with the calcul-

ations for current and size of conductor, but it is necessary always to bear in mind that a transmission line cannot be considered by itself; it must be treated as a part of a complete scheme of transmission and distribution, and the best voltage to use on any given system can generally be arrived at only by a system of trial and error, taking into account the costs of the various parts of the complete system as influenced by alterations in the transmission voltage. No accurate formula can be evolved which would be applicable to all the varied conditions encountered in practical work."

Considering the number of circuits as six, the horsepower per circuit will be 55,800; the length of transmission is 550 miles; substituting in the above formula the pressure of transmission comes out as 158.2 kilovolts. Similarly for four circuits, with a larger amount of power per circuit, the pressure comes out as 171.1 kilovolts.

A list of typical high-tension power transmissions which have been noted in the technical press of the last few years is given on the following page, arranged in the order of their distance of transmission, the operating pressure and the volts per mile being given for each. From this list it is seen that the volts per mile decreases considerably as the length of transmission increases but no definite relation seems to exist between the

two, as was discovered when the volts per mile factor was plotted against the distance in miles. By averaging the values of the volts per mile for the seven systems over a hundred miles long, we get a value of 600 volts per mile, which applied to the Niagara Falls to Chicago transmission would give 330 kilovolts as the operating pressure.

Power Transmissions.

Location.	Miles	Kv	V/mi
Electron to Tacoma, Washington	32	55	1720
Huntington Falls to West Rutland, Vt.	34	44	1293
Lockport to Chicago, Illinois	35	44	1258
Croton Dam to Grand Rapids, Mich.	35	110	3142
Lauchhammer, Germany, from Colliery	35	110	3142
Taylor's Falls to Grand Rapids, Mich.	40	50	1250
Horseshoe Falls to Calgary, Canada	55	55	1000
Douglas, Arizona to Sonora, Mexico	65	44	677
Lac du Bonnet to Winnipeg, Canada	65	60	923
Rogers Dam to Grand Rapids, Mich.	66	72	1090
Shawinigan Falls to Montreal, Canada	85	100	1178
Great Falls to Greenville, S. C.	100	100	1000
Keokuk, Iowa to St. Louis, Mo.	140	100	714
Colgate to Oakland, California	147	60	408
Jucar River to Madrid, Spain	152	70	460
Shoshone to Denver, Colorado	153	100	653
Niagara Falls to Syracuse, New York	160	60	375
Durham to Charlotte, North Carolina	173	100	578

Since no transmission has gone over 140 kilovolts at the present time, although 200 kilovolt apparatus can be obtained, it would seem that such an operating pressure as 300 kilovolts would be out of the question . However, the development along the line of increased pressure has been so rapid in the past that it is quite probable that before long

this pressure will be reached, and therefore it seems desirable to consider it in the preliminary calculations.

After careful consideration of the existing conditions of high-tension power transmission, and the probable achievements in the future, it has been decided to use the values of 100, 150, 200, 250 and 300 kilovolts in the preliminary calculations for transmission pressures, calculating a system for each value of the pressure.

Frequency.

For transmission systems constructed according to present practice the line has a natural frequency which is a function of its length, being equal to one-fourth the velocity of propogation of light or electricity divided by the length of line. The factor of one-fourth enters because the line in this case is equivalent to a quarter wave length. Thus the natural frequency of a 550-mile line is 85 cycles per second. (186,000/(4x550)).

The two standard frequencies in use at the present time are 25 and 60 cycles per second. For 25 cycles the third harmonic is 75 cycles and the fifth harmonic is 125 cycles, while for 60 cycles the third harmonic is 180 and the fifth is 300. In the pransmission under consideration the natural

frequency of the line would be nearest the fundamental for 60 cycles, and nearest the third harmonic for 25 cycles, but would not coincide with either. Since the danger of resonance can readily be eliminated for the third harmonic by inserting reactance coils in the line to prevent any excessive current from flowing, the frequency of 25 cycles is preferable for this reason. The charging current and inductive drop both vary directly as the frequency, and since these factors are great for a very long line it is desirable to use the lower frequency in order to keep them as low as possible. Therefore a frequency of 25 cycles will be used; the cost of power at the generating station was calculated for this value of frequency.

Conductor Material.

The most important parts of a transmission system from the standpoint of operation are the conductors; they also consititute the item of greatest investment from a financial view-point. Copper and aluminum are the two metals which have been in most extensive use for conductors of transmission lines; because of its physical characteristics aluminum is preferred to copper for long lines operating at high potential.

For the same conductivity an aluminum

conductor weighs slightly less than half the copper conductor and has 1.6 times the area of cross-section. The decreased weight decreases the stresses on insulators and towers, and for the same stresses makes longer spans possible with aluminum. The increased area of aluminum gives it greater radiating surface, and the permissible temperature rise is therefore greater than with copper. Further, as will be pointed out when the subject of corona loss is taken up, the larger conductor offers less probability of corona loss than the smaller.

The principal disadvantages of aluminum as compared with copper are its low tensile strength and greater temperature coefficient, which means that for the same allowable sag the spans with aluminum are shorter than those with copper. This difficulty has been overcome by the use of aluminum cable reinforced with steel, which, having about one and one-half times the weight of the equivalent aluminum cable, has about ten times the tensile strength. Further the steel-reinforced aluminum cable has the increased size due to the steel addition, and still has the advantage over copper in that it weighs less than three-fourths as much for the same conductivity.

In calculating the Niagara Falls to Chicago transmission use will therefore be made of the figures for steel-reinforced aluminum cable.

Size of Conductors.

In determining the size of conductors from an economical standpoint two items of cost must be balanced against each other. The one is the annual or overhead charges on the conductors, comprising interest on the investment and depreciation and maintenance, which vary directly as the size of the conductors. The other item is the cost of the power lost in transmission, which varies inversely as the square of the size of conductors. According to Kelvin's law, the most economical condition is that in which these two items of expense balance each other.

The simplest way to determine the economic size of conductor is to plot curves showing the cost of lost power and the annual cost of conductors against the size of conductors. The only losses in high-tension lines affected xxx by the size of conductors are the losses due to resistance drop and corona. For the present it will be assumed that there is no corona loss, in other words, that the cables are spaced sufficiently to avoid corona. It will further be assumed that the loss due to charging current is the same for all sizes of conductors; the error introduced by this assumption is much less than the accuracy to which the final size of conductor can be determined, since the difference between

sizes of commercial cables is in the neighborhood of twenty-five percent. Thus the only factor to be considered in the preliminary calculations is the loss of power due to the resistance drop caused by the load current.

The question arises at this point as to what value of the load current should be used in the calculations. Since the load factor is known to be one-half, it would seem at first sight that this value of load current, namely one-half the maximum, should be used, but further consideration will show that this is not the value of a constant current which would produce the same loss. So it will be assumed that the load curve has the same form-factor as the sine wave, and that the constant current value corresponding to the average loss is equal to the square root of the ~~form~~ load factor, or the current value corresponding to a load of 70.7% of the maximum.

The equivalent continuous current per wire for each circuit at the various high-tension voltages will be

Kilovolts bet. wires	100	150	200	250	300
Current per wire, amps.	170	113.4	85	68.1	56.7

The cost of lost power per kilowatt-year as shown by the curves of Fig. 7 will be

Kilovolts	100	150	200	250	300
Cost of power	$10.80	11.05	11.35	11.60	11.90

The following data on steel-reinforced aluminum cable was used in calculating the conductor charges ; this data was derived from the data on plain aluminum cable by using the relation that weight of reinforced cable is one and one-half times that of the plain, the resistance being the same, (since conductivity of steel is neglected), and the cost of the aluminum-steel is nineteen cents per pound when the Aluminum plain is twenty-five cents per pound.

Alum. Area Cir. Mils	Per 1000 feet. Weight #	Annual cost	Res. ohms
800,000	1105	$12.60	.0209
700,000	965	10.98	.0239
600,000	829	9.49	.0279
500,000	690	7.86	.0335
400,000	552	6.30	.0418
300,000	414	4.71	.0558
211,600	293	3.34	.0790
105,500	145	1.66	.1585

The costs of lost power and charges on conductors were plotted in the curves of Fig. 9, and from the intersections of the two cost curves the proper size of cable was determined, the next largest commercial size being taken.

Kv	Alum. area c.m. (cur)	Tot. area c.m.	Diam.	Str.	Actual c.m. Aluminum	Steel
100	575,000	715,500	0.97"	37	580,100	135,400
150	390,000	477,000	0.78	19	387,500	89,500
200	292,000	397,500	0.72	19	323,000	74,500
250	240,000	336,420	0.66	7	280,320	56,100
300	202,000	266,800	0.58	7	222,400	44,400
200	445,000	556,500	0.86	37	451,000	105,500

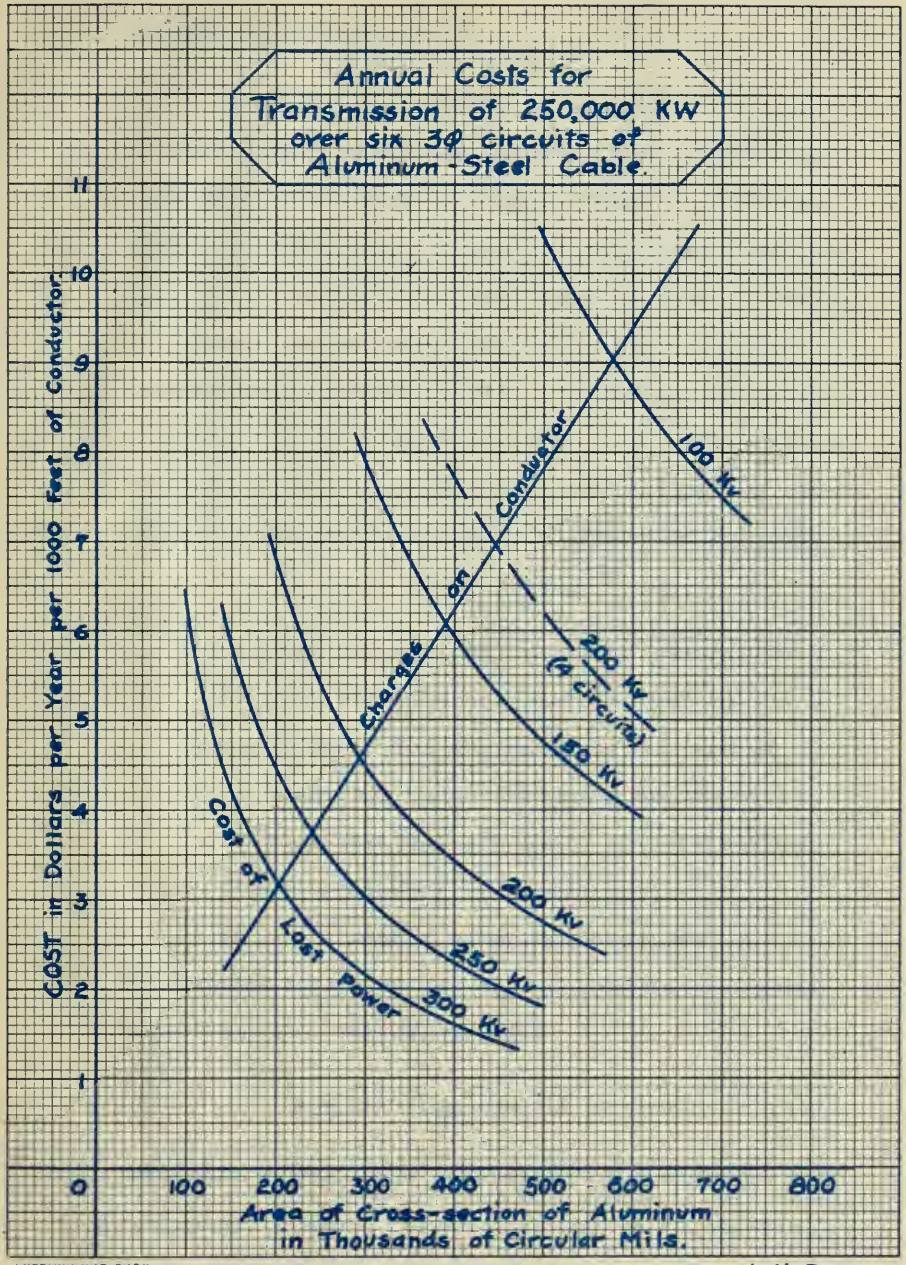

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Fig. 9.

Separation of Conductors.

In the separation or spacing of conductors for high-tension transmission the distance between conductors must be greater than the striking distance through air of the potential employed, and also great enough to prevent loss of power by corona. The former may be taken as the maximum distance between sharp needle points over which the potential will cause a spark to jump. The latter is a function of the size of conductor, and may be calculated from Peek's formula, which is as follows:

$$e' = m\, g\, r \log_e \frac{s}{r}$$

where

e' is the value of kilovolts to neutral to just start corona, (e' is .577 e)

m is a factor for character of surface of conductor, lowest value 0.83 for cable.

g is the potential gradient, 21.1 kv per cm.

r is the radius of the conductor,

s is the distance between conductors.

Solving the equation for s, and changing to common logarithms and inches, we have

$$s = \log^{-1}\left(\frac{e'}{102.5\, r} + \log r\right)$$

From this formula the separation of conductors necessary to avoid corona loss may be calculated. Taking the values of striking distances from the A. I. E. E. Rules, and calculating values of s from

the formula for the various voltages assumed, we get the results as shown in the following table:

e	e'	Strik. Dist.	s	r	
100	57.7	9.6"	6.9 in.	0.49"	
150	86.6	15.0"	57.5 in.	0.39"	
200	115.4	20.3"	40.0 ft.	0.36"	6 circuits
250	144.3	25.5"	514 ft.	0.33"	
300	173.2	30.5"	28,100 ft.	0.29"	
200	115.4		14.8 ft.	0.43"	4 circuits

From these results it is seen that the spacing to avoid striking-over is proportional to the voltage, and is well within commercial possibilities of separation, while the 200, 250 and 300-kilovolts lines are out of consideration if the spacing for no corona loss must be given them. While a line can be operated with spacing such that corona loss takes place between the conductors, it is not desirable to consider such a proposition in the present discussion, and for that reason the only lines considered for a six-circuit transmission will be the 100 and the 150-kilovolt, while the 200-kilovolt will be calculated for four circuits.

Insulators.

For all operating potentials over sixty kilovolts the suspension insulator is used; in fact, it was the advent of the suspension insulator which made extra high-tension transmission possible. It

would appear that the suspension insulator could be used for any voltage by simply adding more discs, and increasing the length of the string in proportion to the voltage for the higher voltages. However, it has been found that with a number of the suspension type insulator units in series, the drop over each insulator unit is not the same, but that the unit nearest the line receives a much greater proportion of the total impressed voltage than the unit nearest the tower. These characteristics are shown in Fig. 10, which shows the arc-over voltages for both dry and wet tests. It is there shown that after a certain number of units have made up the string, the addition of more units hardly affects the arc-over voltage when dry; this is because the insulator unit nearest the line is over-stressed since it carries the charging current for all the others, and the potential drop over it is conseqently greater than over the others. It will be further noted that the wet test arc-over voltage is proportional to the number of units in series, and that after a certain number compose the string, the wet test arc-over occurs at a <u>higher</u> voltage than the dry test arc-over; in other words, the danger of arc-over is less with the wet insulator than with the dry. This is because the effect of the moisture is to equalize the current and the drop over each insulator unit.

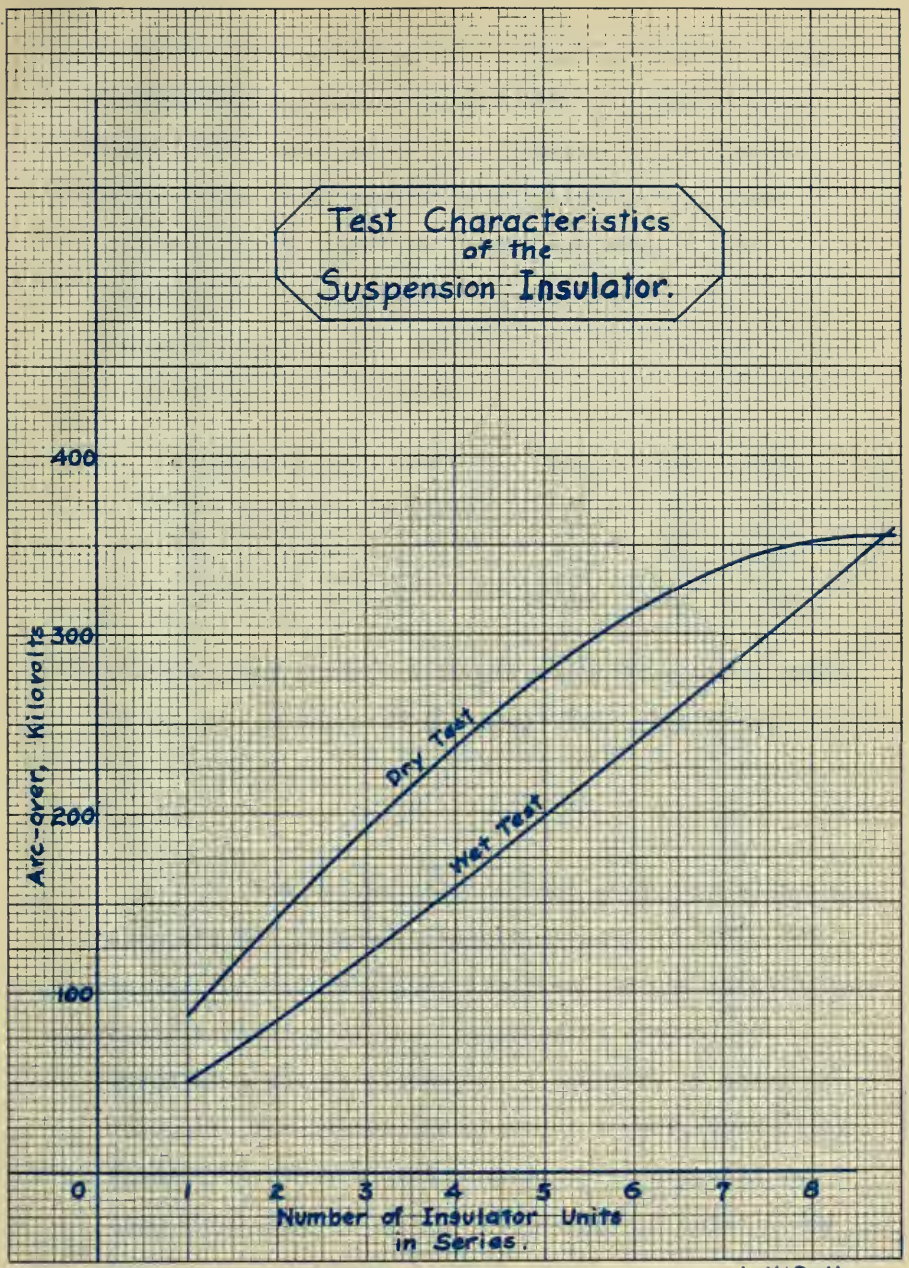

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Fig. 10.

In selecting the insulators for the transmissions under discussion it will be assumed that each string must stand the pressure between wires with a factor of safety of at least two. This means that one line can become grounded without subjecting the insulators on the other lines to a voltage greater than one-half the test voltage at which they will arc over.

Kilovolts bet. lines	100	150	200
No. of units in string	6	8	8
Wet arc-over, kv	240	320	480
Dry arc-over, kv	310	350	420
Factor of safety	2.4	2.1	2.1
Price per string	$6.00	8.00	16.00

The insulators for the 200-kilovolt line are assumed to be of special design, hence their higher cost.

Towers.

The mechanical problems connected with the strength and height of towers, length of span, and sag of conductors are as important as the electrical characteristics of the transmission system, but these will not be discussed. However, in order to determine the number and costs of towers, some assum- assumptions, based upon standard practice, will be made regarding the height and weight of towers, and the span or distance between towers.

The conductors are to be arranged on the

towers so that the three wires of one circuit lie in a vertical plane, each tower to carry two circuits, one on each side. This means that each tower will have three cross arms of equal length, and spaced apart a distance equal to the distance between conductors. The height of tower as given below is the distance from the ground to the highest cross-arm.

The length of span will be taken as 1600 feet for the steel-reinforced aluminum cable, this figure being declared entirely practical for span length by the engineers of the Aluminum Company of America. Thus the number of towers per line would be 1813 for 550 miles, to which number an addition of about ten percent will be made to cover the cost of special towers, strain towers, etc., making the total number of towers per line 2000.

The tower data given below refer to a type of tower similar to the Milliken tower in use by the Great Western Power Company.

Kv	Height Feet	Weight pounds	Cost
100	70	3500	$122.50
150	75	3700	129.50
200	80	4000	140.00

The cost is calculated at 3.5 cents per pound.

Cost of Transmission System.

1. Right-of-way.

In figuring the cost of the right-of-way

the width has been made such that the distance between tower lines is great enough to allow one tower line to overturn without interfering with the others

Data on Right-ofway.

Kilovolts bet. lines	100	150	200
No. of tower lines	3	3	2
Height of towers	70	75	80
Width of right-of-way, ft.	195	210	125
Area, in square miles	20.3	21.9	13.0
in acres	13,000	14,000	8,320
Cost of right-of-way	$1300,000	1400,000	832,000

2. Towers.

Kv	No.	Price	Tot. Cost
100	6000	$122.50	$735,000
150	6000	129.50	777,500
200	4000	140.00	560,000

3. Conductors.

Kv	No.	Size c. m.	Weight per 1000'	Tot. weight pounds	Total Cost
100	18	715,500	907	47,400,000	$9,000,000
150	18	477,000	603	31,500,000	5,900,000
200	12	556,500	706	24,600,000	4,680,000

4. Insulators.

Kv	per String	per Tower	no. Towers	Tot. cost
100	$6.00	$36.00	6000	$216,000
150	8.00	48.00	6000	288,000
200	16.00	96.00	4000	384,000

Installation Costs per Tower:

Excavation and setting of footings	$20
Assembling towers	10
Erecting towers	5
Haulage of towers	5
Haulage of line materials	20
Stringing cable	25
Engineering and surveys	40
Overhead Charges	20
Contractors' profit	5
Total cost per tower	$150

5. Installation Costs.

Kv	No. of Towers	Total cost
100	6000	$900,000
150	6000	900,000
200	4000	600,000

Total capital costs of transmission:

Kilovolts	100	150	200
1. Right-of-way	$1,300,000	1,400,000	832,000
2. Towers	735,000	777,500	560,000
3. Conductors	9,000,000	5,900,000	4,680,000
4. Insulators	216,000	288,000	384,000
5. Installation	900,000	900,000	600,000
	12,151,000	9,265,500	7,056,000
Eng. & Cont. 10%	1,215,000	926,500	705,600
	$13, 366,000	10,192,000	7,761,600

Taking average depreciation and maintenace value of 2%, with interest at 4%, annual charges are 6% of capital cost. Cost of patrolling line taken as $75 per mile per annum.

Annual Charges:

Kilovolts	100	150	200
Interest and dep.	$796,000	611,000	466,000
Patrol	412,000	412,000	412,000
	$1208,000	1023,000	878,000

Line Constants.

In considering the inductance of a circuit composed of steel-reinforced aluminum cable it is found that the inductance is higher than that of an equivalent plain aluminum cable. From experiments made by the Aluminum Company of America , it has been found that the inductance of a circuit composed of steel-reinforced aluminum is practically the same as that of the equivalent circuit of copper having the smaller conductor. Therefore in calculating the inductances of the various circuits the value of the radius of the conductor will be the value of the equivalent copper conductor.

The formula used to calculate the inductance is

$$L = .03048 \left(.46 + 4.61 \log \frac{s}{r} \right)$$

where L is the inductance in millihenrys per 1000'

s is the distance between conductors,

r is the radius of equivalent copper conductor

This formula is based upon the assumption that the cables are transposed in such a way that each one occupies a middle position for one-third the length of line and an outside position for the remaining two-thirds.

The product of the capacity and inductance of any circuit is a constant. Hence the capacity may be calculated from the inductance, by the formula

$$C = 286\ M^2 / L \times 10^{10}$$

where C is the capacity in farads, L is the inductance in henrys, and M is the distance in miles.

The charging current is calculated from the formula

$$I_c = .00628\ f\ E_n\ C$$

where I_c is the charging current in amperes, f is the frequency in cycles per second, and E_n is the effective voltage to neutral in kilovolts, C being the capacity to neutral in microfarads.

From the calculations the constants for the three lines are

Kilovolts	100	150	200
Diam. of equiv. copper cable (2r)	0.68"	0.56"	0.60"
Spacing of conductors (s)	120"	150"	180"
Inductance per cable, millihenrys	1080	1155	1175
Capacity per cable, microfarads	8.01	7.49	7.35
Resistance per cable, ohms	83.7	125.5	107.5
Inductive reactance, ohms	170	181	185
Capacity reactance, ohms	795	850	866
Charging current, amperes	72.6	101.9	133.0

Regulation.

In considering the regulation of such a long transmission line it is found that at no-load the potential at the receiver end is greater than that that at the generator end because of the rise in voltage due to the leading charging curr ent. At full-load, from the constants found above, the generator voltage is not at all sufficient to overcome the reactance voltage generated in the line when

full-load current is flowing though it. This does not mean that the transmission can not operate, but it is a condition which requires additional inductance to be placed in the line to neutralize the effect of the capacity. This may be done by shunting reactance coils across the line at intervals to take a quadrature lagging current which will exactly neutralize the leading current taken to charge the line.

The rise in voltage as the load is removed is compensated for by arranging to feed part of the charging current from the receiver end of the line; this causes the voltage to drop at that end, with the result that the voltage at the middle of the line will rise to a value above either end, while the receiver voltage may be kept constant. Hence, the matter of regulation becomes one of operation, since all control apparatus may be located at the receiver end and the voltage there kept constant.

Under the best operating conditions the voltage at the sub-station end will be the impressed voltage minus the IR drop in the line at full-load:

Kilovolts	100	150	200
IR drop at full-load per line	20	20	21
Drop per circuit, three-phase	35	35	37
Kilovolts at receiver	65	115	163

Power Delivered to Sub-station.

The power delivered to the sub-station

will be the power put into the line minus the line loss minus about one percent for leakage, which gives the results:

Kv	Kw Power
100	160,000
150	190,000
200	185,000

THE SUBSTATION.

The sub-station at Chicago will be a transformer station in duplicate of the one at Niagara Falls. In order to limit the destructiveness of an arc-over or short-circuit on any of the circuits the generators and transformers at the station will be grouped into units and all paralleling will be done at the receiver end. In other words, no line can receive power from any other generator unit than its own, except that power can come from the sub-station over some other line, in which case the line phenomena will limit its destructiveness.

Cost of Substation.

The cost of the sub-station was calculated from the data of Fig. 1 to be $2,043,000 for the 100-kilovolt station; assuming the cost to be in direct proportion to the voltage, the 150-kilovolt station would cost $3,065,000 and the 200-kilovolt sub-station $4,086,000.

Cost of Transformation.

Assuming the annual charges on the sub-stations to be nine percent of the capital cost, a value derived from the curve of Fig. 4, after deducting the ten percent item for rental of water, we have the annual cost of transformation as given in

the following table:

Kv	Cost
100	$184,000
150	276,000
200	367,000

Net Power at Sub-station.

Assuming transformer losses at about 2 1/2 percent the net amount of power available at the low tension bus-bars of the substation will be

Kv	Kw Power
100	156,000
150	185,000
200	180,000

Net Cost of Power at Chicago.

The total operating expenses of the system are as follows:

Kilovolts	100	150	200
Generating plant	$1,975,000	2,030,000	2,080,000
Transmission line	1,208,000	1,023,000	878,000
Sub-station	184,000	276,000	367,000
	$3,367,000	3,329,000	3,325,000
Net power, Kilowatts	156,000	185,000	180,000
Cost of power per kw-year, 100% load fact.	$21.56	18.00	18.48
50% load factor	43.12	36.00	36.96
Cents per kwh	0.492	0.411	0.422

CONCLUSION.

The results obtained show that the 150-kilovolt line is the most economical of the three considered for the transmission of Niagara Falls power to Chicago. Thus it is shown that notwithstanding the fact that the higher voltage lowers the cost of transmission considerably, when the cost of generation and transformation are also considered the net cost is not always in favor of the highest voltage.

In a comparative sense the figures presented have value since all calculations were made upon the same assumptions, except that the 200-kilovolt line had the advantage of one less tower line; however, in a strictly practical sense the figures presented have only an approximate value in giving an idea of the cost of Niagara Falls power in Chicago, since an accurate determination of such a matter cannot be made in the general way here pursued.

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